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Enhanced decentralized PI control for fluidized bed combustor via advanced disturbance observer

Li Sun [a,*], Donghai Li [a], Kwang Y. Lee [b]

[a] The State Key Lab of Power Systems, Department of Thermal Engineering, Tsinghua University, Beijing 100084, PR China
[b] Department of Electrical and Computer Engineering, Baylor University, Waco, TX 76798-7356, USA

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ABSTRACT

Motivation of this paper is to propose an engineering friendly control strategy to handle the various difficulties in fluidized bed combustor (FBC). The control objectives of FBC and the difficulties arisen from nonlinear dynamics, frequent disturbances and strong coupling are first formulated. The capability of the disturbance observer (DOB) to handle the nonlinearity and disturbances is analyzed and the decoupling effect of DOB is revealed in terms of equivalent transfer function. For the power loop, a robust loop shaping design method is proposed to balance the performance and robustness of DOB. For the temperature loop, the DOB filter is designed based on H_∞ optimization. Abilities of DOB are confirmed by numerical simulations. A water tank experiment is designed to show the simplicity of implementing DOB in an industrial Distributed Control System. Finally, a global simulation on the FBC process demonstrates that, compared with the conventional PI scheme, the DOB-enhanced PI strategy achieves overall improvement and can even be comparable with the complex Model Predictive Control in some aspects.

1. Introduction

Fluidized bed combustor (FBC) boilers have been developed increasingly in recent decades as an advanced clean coal technology (Ozdemir, Hepbasli, & Eskin, 2010). It facilitates burning of a wide variety of fuels with high combustion efficiency, especially for low-grade coal. The FBC was developed to strive for a combustion condition, under which the pollutant emissions can be reduced significantly without a chemical scrubber. The burning temperature of such technology is within the range of 750–950 °C, exactly out of the range where nitrogen oxides form so that the amount of NO_x emission is just 1/3–1/4 of that in a conventional pulverized coal plant. Thus, bed temperature regulation, along with strong capacity of load tracking, is critical to reduce pollutant emissions.

However, essentially, the FBC can be described as a typical multivariable system with almost all the difficulties found in process control, i.e., nonlinearities, strong couplings, various internal and external disturbances, non-minimum phase (NMP), and time delay. These difficulties result in enormous hardships on controller design. The conventional decentralized proportional-integral (PI) control scheme is thus powerless in achieving satisfactory performance under such extreme circumstances. Many researchers (Aygun, Demirel, & Cernat, 2012; Hadavand, Jalali, & Famouri, 2008; Leimbach, 2012; Ćojbašić, Nikolić, Ćirić, & Ćojbaši, 2011; Sun, Pan, & Shen, 2013; Zhang, Feng, Lu, & Xiang, 2008) have worked on various advanced control schemes for FBC processes to accommodate some of the difficulties. Aygun and Demirel proposed a particle swarm optimization (PSO) algorithm to optimize the proportional-integral-derivative (PID) controllers for the bed temperature (Aygun et al., 2012). An H_∞ control algorithm based on linear matrix inequalities (LMI) was also proposed in Hadavand et al., (2008) to improve the performance of the bed temperature. However, strong interactions between power and bed temperature were not considered. Intelligent control strategies (Leimbach, 2012; Ćojbašić et al., 2011) were also introduced to facilitate the reference tracking of FBC boiler. But, there are few relevant literatures taking into an explicit consideration of the NMP characteristics in the FBC system. Model predictive control (MPC), which is widely recognized as a powerful strategy in handling decoupling, reference tracking and time delays, also received considerable attention in the FBC control (Sun et al., 2013; Zhang et al., 2008). However, the conventional or improved MPCs are usually subject to a great deal of calculation, which makes it not feasible for the contemporary Distributed Control System (DCS) in power plant. Compared with the

* Corresponding author.
E-mail address: sunli12@mails.tsinghua.edu.cn (L. Sun).

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conventional PI controller, MPC usually requires an additional computer, such as high-performance Programmable Automation Controller (PAC), to calculate the control signals and then communicate with DCS. Inevitably, it brings more hardware uncertainties into the system, which is unacceptable for practitioners because they always consider the long-term reliability as their primary concern.

The long-term running of FBC boiler is also subject to various disturbances, such as variations in the calorific value of feed coal, changing moisture content of the primary air, and slagging or erosion on the water wall. These disturbances, together with plant perturbations under different working conditions, deteriorate the performance of the FBC process. Although previous researches mainly focused on the reference tracking issue, they paid little attention to the disturbance rejection.

As is well known, the basic PID controller, actually in most cases PI controller, is still dominant in power generation for its simplicity and ease of use (Xue, Li, & Gao, 2010). This paper attempts to accommodate all the aforementioned control difficulties within the framework of conventional decentralized PI scheme with the assistance of the disturbance observer (DOB) (Umeno & Hori, 1991). While PI controllers are responsible for the zero-offset reference tracking, the other control difficulties are expected to be handled by the DOB, whose enhancement role is embodied as:

- The quasi feed-forward compensator which can estimate the disturbances and then reject it actively;
- The plant re-shaper which can recover the nonlinear plant as the nominal linear model in the wide operating range;
- The dynamic decoupler which requires lower modeling accuracy than conventional methods.

With the advantages above, the DOB approaches have been widely utilized in many practical applications (see Chen, Yang, Li, and Li (2009), Li, Qiu, Ji, Zhu, and Li (2011), Liu Chen, and Andrews (2012) and references therein). In a traditional explanation of the DOB's decoupling ability, interaction is assumed as a part of the total disturbance, which should be observed by DOB and then rejected. This paper will clarify the decoupling ability by bridging DOB to the well-known inverted decoupling structure.

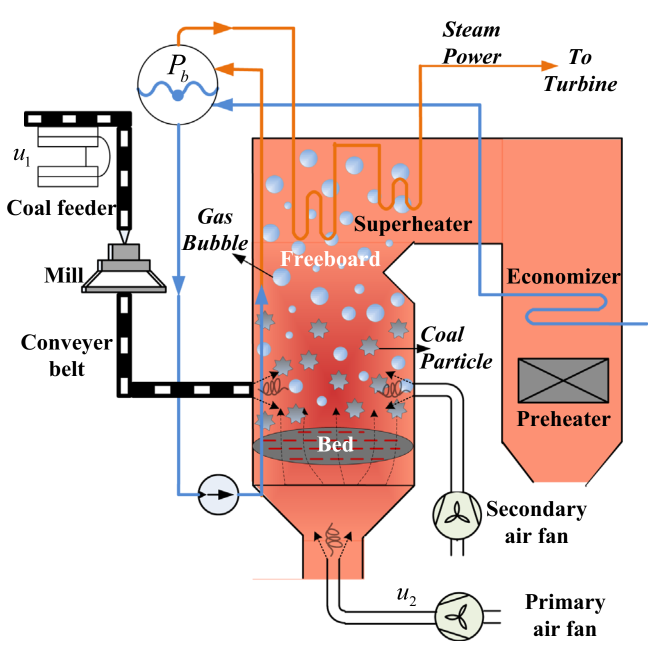

Fig. 1. A schematic of a typical fluidized bed combustor.

Considering the slow dynamics, time delay and NMP feature of the FBC boiler, the standard DOB is modified to achieve an improved performance. A water tank experiment is carried out to test the realizability of the proposed strategy in the DCS.

The feature that makes the proposed method distinct from other advanced algorithms is attributed to the engineering friendliness. The proposed strategy needs negligible amount of computation and is completely compatible with already existing control systems. The DOB can be embedded into the DCS in a bumpless manner without the necessity of retuning the PI parameters. The remainder of the paper is organized as follows: the control difficulties in the FBC system are formulated in Section 2. Section 3 analyzes the capability of DOB in dealing with the disturbances, nonlinearity and coupling as well as the time delay and NMP characteristics. In Section 4, a numerical simulation and experimental test is given to confirm the effectiveness and implementability of DOB. A comparative simulation of the FBC application is carried out in Section 5 and conclusions are drawn in Section 6.

2. Problem formulation

2.1. Overview of fluidized Bed combustion technology

Fluidized bed suspends coal particles on continuous updraft of primary air during the combustion process, which leads to an intensive mixing of solid fuel and gas. The turbulent condition, similar to a bubbling fluid, leads to a higher efficiency for the chemical reactions and heat transfer. The schematic of a FBC boiler is shown in Fig. 1. A mixture of inert/sorbent bed material and solid fuel is fluidized by the primary air entering from below. Secondary air is injected above the fuel bed to ensure complete gas burning out. However the total amount of air should be limited due to economic efficiency. The heat released in combustion is captured by heat exchangers to convert the circulating water to the steam.

2.2. Control objectives

The past two decades has witnessed a rapid development of the renewable energy generation. However the intermittent characteristics of the sustainable source make it more challenging to maintain power grid stability. The conventional fossil fuel generation should thus bear more responsibility in the primary frequency regulation of power grid. In light of this background, the control objectives of FBC boiler is listed below in a descending order of importance:

I. The thermal power output of the boiler should track the reference load commanded by the turbine.
II. The bed temperature should be adjusted correspondingly to a reasonable value.
III. The power output and the bed temperature should be as insensitive as possible to the furnace disturbances.

The first requirement is set for the real-time balance of the power grid or microgrid and the second for the environmental and economic purposes. Although the temperature range between 750 °C and 950 °C can prevent the formation of NO_x, a particular value is usually preferred for the combustion efficiency. Now the third requirement is attracting considerable attention in engineering practice but less from the academic community. Without proper treatment, the variation of the coal quality, i.e., the heat value perturbation, may make the boiler outputs deviate from the desired value significantly.